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REASSESSMENT OF HUMAN PERFORMANCE PARAMETER ESTIMATES FOR RESPIRATORY PROTECTION DESIGN AND DEVELOPMENT

David M. Caretti
Karen M. Coyne

RESEARCH AND TECHNOLOGY DIRECTORATE

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14. ABSTRACT

The key to ensuring that rational respirator technology solutions are possible and acceptable to the user community is the knowledge that each option has a sound scientific basis. Historical mask wear human performance research offers useful, albeit limited, insights on the relationships between design parameters and performance. The purposes of the current task were to review and revise the existing human performance capabilities and mask design parameters databases and to derive new algorithms to more accurately define human performance capabilities related to respirator wear. The results reaffirm that much of the basic psychophysiological data needed to enhance respirator design requirements remains elusive. The main data gaps across all performance capabilities include little or no knowledge concerning the relationships among respirator design components and performance and the impacts of design parameters on task performance across different work intensities. The impacts of mask design on subjective comfort and subsequent task performance is the capability area with the least amount of reliable information. In this regard, research needs to continue to advance the knowledge base to ensure that next generation respirator designs can be based on robust human factors data.

15. SUBJECT TERMS

Respirator	Breathing resistance	Head borne mass	Vision
Human performance	Speech intelligibility	Performance estimates	Comfort

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PREFACE

The work described in this report was authorized under Project No. BO07PRO100, Exploratory Development. This work was started in November 2006 and completed in September 2007.

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1. INTRODUCTION

The guiding principles for respirator design are to protect the wearer from airborne contaminants and to reduce the human psychophysiological burdens associated with respirator wear. Measurable progress has been realized over the years toward enhancing the protective capabilities of military respirators. However, such advancements appear to be of little support to end users who regularly register complaints about breathing difficulties, communication problems, and discomfort experienced during mask wear. The historical persistence of these types of user reports suggest that mask wear human factors parameters are second thoughts in the military mask design process. The reality of the situation, though, is that human factors are in the forefront of the process but the goals of reduced user encumbrance are often inadequately defined, are in conflict with the primary need to protect the end users, or create other unintended changes in operational usage that are unacceptable to military users. An example of the latter is the use of a powered air supply that could substantially improve breathing difficulties, help with thermal discomfort, and alleviate eyepiece fogging in certain environments. However, blowers require batteries and create noise, two consequences that are generally deemed unacceptable for long-term operational performance (i.e., problems with battery life and replacements) and covertness. Nevertheless, technology solutions for enhanced user performance associated with respirator wear continue to be pursued and proposed with each new mask design program.

The key to ensuring that rational technology solutions are possible and acceptable to the user community is the knowledge that each option has a sound scientific basis. Historical mask wear human performance research offers useful, albeit limited, insights on the relationships between design parameters and performance. The Respirator Encumbrance Model (REM) attempted to build upon such information by critically evaluating human performance and performance parameter related references associated with respiratory protection. The overriding goal of the REM was to provide mask designers the capability to predict operational task performance of soldiers/sailors/airmen/marines wearing respirators based on the physical, material, and design characteristics of the respirator system and the psychophysiological requirements of select military tasks. One of the primary components of the REM was a database of human performance capabilities determined to be influenced by respirator wear. The REM also included a database of mask design parameters deemed to have direct influence on human performance. Relationships among these and the human performance capabilities were used to derive performance estimates due to respirator design characteristics. The purposes of the current task were to review and revise the human performance capabilities and mask design parameters databases developed for the REM based on the known limitations of the application and to revise or derive new algorithms to more accurately define human performance capabilities related to respirator wear.

2. METHODS

2.1 Review of Human Performance Capabilities.

The human performance capabilities database of the REM included 20 capabilities, 15 of which were developed for the Operational Requirements-based Casualty Assessment (ORCA) model and an additional five determined to be needed to relate the information provided by the ORCA to the REM database.[1] A brief description of each of the human performance capabilities is presented in Table 1. Of these capabilities, appropriate respirator wear performance data were available to derive performance algorithms for only the following: comfort, dead space, fatigue-endurance, expiratory and inspiratory resistance, high frequency hearing threshold, visual and peripheral field of view, and speech intelligibility. The ability to develop meaningful performance algorithms for the remaining capabilities was hindered by a lack of empirical data, the definition of ORCA performance scales (either too broad or very limited), or the failure to establish any meaningful relationships between a capability and any mask design parameters.

A review of the final REM human performance capabilities database was initiated as part of the current effort. This review included literature searches for additional data relevant to each of the 20 capabilities presented in Table 1, a critical re-evaluation of both previous and new data sources, and establishment of a new set of scientifically sound human performance capabilities related to respirator wear. Finally, a review of the general physiological mechanisms paramount to human performance over the range of low to high work intensities was completed.

2.2 Development of Human Performance Algorithms for Respirator Wear.

Establishing meaningful estimates of performance under conditions of respirator wear requires linkages between design components and performance. As such, a comprehensive list of mask design parameters purported to have direct influence on psychophysiological performance during respirator wear was developed as part of the REM application (Table 2). The relevance and importance of each of the design parameters was reassessed for this effort.

Of the eight performance algorithms utilized in the REM application, only five had validated linkages between performance and specific respirator components. Algorithm development was restricted primarily by the limited availability of data linking performance with design components. Additional data were reviewed and analyzed under the current effort as an attempt to either revise or redefine existing human performance estimates and to develop new performance prediction algorithms.

3. INTERIM RESULTS

3.1 Physiological Performance Requirements of Respirator Wear.

The basic model of work performance time limitations as a function of work rate initially proposed by Johnson and Cummings[2] served as a basis for the Fatigue-endurance REM performance capability. This model suggests that the length of time an individual is able to perform increases as the work rate decreases (Figure 1). Under this concept, performance times of 5-15 min should result in maximal sensitivity to respiratory factors, 15-240 min should

result in maximum sensitivity to thermal factors, and times greater than 2 hr should result in maximum sensitivity to psychological factors.

Table 1. REM Human Performance Capabilities

Human Performance Capability	Description/Definition
Auditory mental processing	The amount of auditory processing that a situation entails ranging from registering to interpreting a particular sound
Balance	Postural stability required
Binauralism	Does/does not require two ears
Biomechanics/Head & neck movement	Movement that is required of the head and neck
Cognitive mental processing	The amount of cognitive processing that a situation entails ranging from simple association to calculation and conversion
Comfort	The relationship between sources of psychological distress and mask components
Dead space	Volume of inspired air that is re-inhaled from the preceding exhalation
Depth perception/Visual binocularism	Vision in both eyes is required to form a single, fused, stereoscopic image
Fatigue-endurance	Time to run 2 miles
Field of view sight	Field of view when using a rifle sight or similar sighting device
Expiratory resistance	Resistance to expired airflow imposed by the respirator and its expiratory valves/components
Visual and peripheral field of view	Visual field of view
Hearing threshold-high frequency	Minimum decibel level required to detect high frequency sounds (> 1 kHz) some distance away
Hearing threshold-low frequency	Minimum decibel level required to detect low frequency sounds (≤ 1 kHz) some distance away
Inspiratory resistance	External resistance to inspired airflow imposed by the respirator and its filter element(s)
Psychomotor mental processing	The amount of psychomotor processing that a situation entails ranging from speech generation to serial manipulation
Speech intelligibility	Level of communication required by the intelligibility scale
Thermal burden	Physiological impact of relationship between mask materials and environmental factors
Static visual acuity	Clarity of vision required to see stationary objects of different sizes at different distances
Visual mental processing	The amount of visual processing that a situation entails ranging from detection to monitoring of an object

Table 2. REM Mask Design Parameters

• Lens shape	• Field of view	• Lens area
• Lens location	• Lens orientation	• Lens curvature
• Lens width	• Communication area	• Voicemitter shape
• Communication	• Communication location	• Communication orientation
• Voicemitter material	• Filter area	• Filter thickness
• Filter shape	• Filter location	• Filter pressure drop
• Filter orientation	• Inlet valve area	• Inlet valve shape
• Inlet valve location	• Inlet valve pressure drop	• Inlet valve orientation
• Outlet valve area	• Outlet valve shape	• Outlet valve location
• Outlet valve pressure drop	• Outlet valve orientation	• Nosecup area
• Nosecup shape	• Nosecup location	• Nosecup orientation
• Nosecup area	• Nosecup shape	• Nosecup location
• Nosecup orientation	• Dead space volume	• Facepiece material
• Mask suspension	• Canister weight	• Profile (canister)
• Drink tube shape	• Drink tube flow rate	• Drink tube area
• Drink tube location	• Drink tube orientation	• Drink tube length
• Drink tube diameter	• Hood thickness	• Hood material

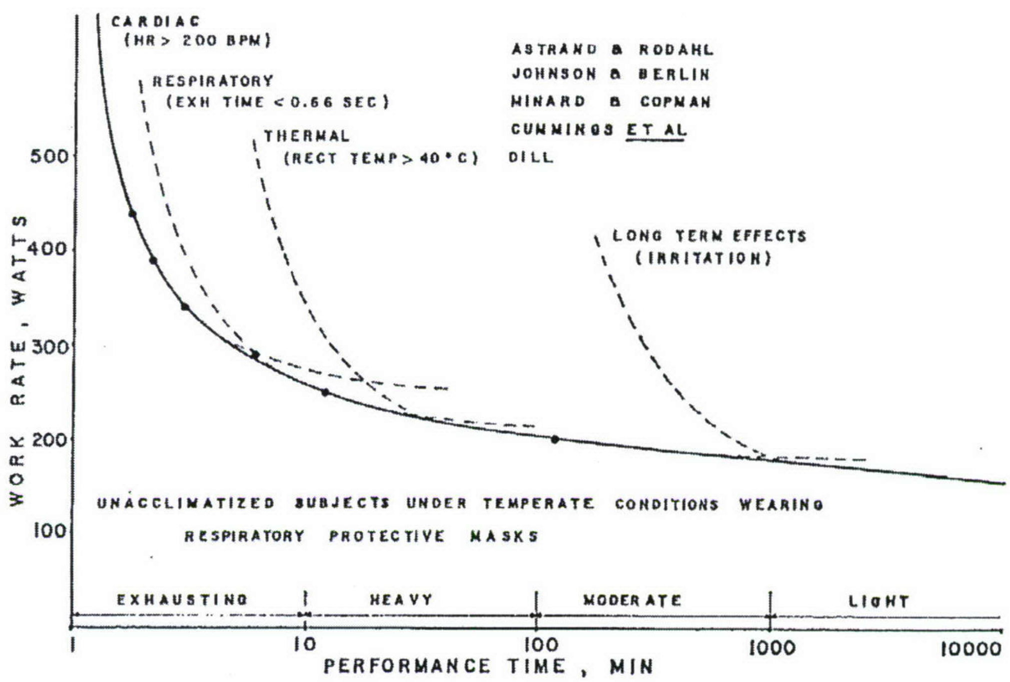


Figure 1. Working Model of Stress Limitations under Conditions of Exercise and Respirator Wear (adapted from Johnson and Cummings, 1975)

The Johnson and Cummings[2] working model was implemented in the REM application by categorization of task workloads based on a Fatigue-endurance scale value (Table 3) and applying related capability algorithms to estimate task performance with mask wear compared to performance without a mask. However, several limitations with the REM categorization of task workloads based on the scale in Table 3 have been realized upon further review. First off, the generally broad scale values of the Fatigue-endurance capability did not provide a high degree of resolution for task workloads between low and moderate or moderate to high intensity physical work. Secondly, moderate intensity work loads were permitted to be categorized as one of two scale values, which allowed for some tasks to be rated the same as high intensity work (value = 2). Additionally, the relative rates of maximal aerobic capacity ($\%\dot{V}O_2max$) used to define the work load categories failed to match widely accepted norms used for similarly defined work intensities. For example, Johnson et al.[3] equated heavy work as relative load in excess of 95% $\dot{V}O_2max$ and moderate work as 70% $\dot{V}O_2max$, compared to the greater than 50% $\dot{V}O_2max$ and 33 – 48% $\dot{V}O_2max$ values utilized by the REM for respective categories. Finally, the only performance capability algorithms that were used in conjunction with the Fatigue-endurance capability were inspiratory resistance, expiratory resistance, comfort, and dead space.

Table 3. REM Fatigue-Endurance Capability Scale Values

Scale value	$\%\dot{V}O_2max$	Description	Principal Stressor(s)
0	0	Low intensity/can be tolerated indefinitely	Thermal/Psychological
1 or 2	32.7 – 47.6	Moderate intensity	Respiratory/Thermal
> 2	≥ 50.6	High intensity	Respiratory

3.2 Updated Human Performance Capabilities.

Assessment of the current applicability and limitations for each of the original REM human performance capabilities to performance under respirator wear conditions resulted in the following observations.

3.2.1 Auditory Mental Processing.

Head borne protective equipment can be expected to distort the binaural and monaural differences of time, level and spectrum that provide the cues for auditory mental processing. The limited data associated with sound localization or directional hearing with respirators and hoods shows only small losses of speech intelligibility for speech generated either directly in front of listeners or directly behind them.[4] Losses of directional binaural sensitivity at angles other than the midline appear to be greater. However, no new research data exists to map human performance during respirator wear to the workload scale used in the REM application or to enhance the knowledge base.

3.2.2 Balance.

Postural stability is affected by vestibular and proprioceptive input. With respirator wear only proprioceptive inputs appear to be relevant.[5] Although center of mass of head borne equipment may impact neck strain and comfort, there is little evidence to suggest that postural stability will be measurably altered due to such a small perturbation as respirator wear. Relevant data concerning impacts of center of mass of respirator and head borne IPE wear on stability, comfort, and acceptability are currently being obtained in a collaborative study between ECBC and the U.S. Air Force (USAF). In brief, the primary objectives of this study are to quantify (1) the degradation of upper thorax and neck muscle response (fatigue) and (2) the degradation of performance (measured as a function of mobility (walking), ability to work on a computerized device, and ability to complete typical first responder tasks (bending, kneeling, lifting, etc.)), due to the wearing of air purifying respirators of varied mass properties with and without protective helmets. The applicability of the research results from the ECBC – USAF study toward establishing relationships between respirator postural stability and task performance is unknown at this time. Other potential data needed to quantify the impacts that respirator wear may have on balance and task performance were not found in the most recent literature search.

3.2.3 Binauralism.

The original scale values for binauralism (0 – does not require two ears; 1 – requires two ears) limited the applicability of the capability to the REM. The data available for auditory mental processing do not support the notion that wearing a respirator/hood combination will prevent users from having both ears available for completion of any work tasks. No new information was found to change the applicability of this performance capability to conditions of respirator wear.

3.2.4 Biomechanics/Head and Neck Movement.

Published biomechanics data indicates that head flexion and rotation are restricted due to respirator wear.[6] However, the impacts of a respirator on head movement could not be mapped to the REM capability scale that limited performance to only two choices – no head movement required or head movement required. Likewise, the data does not quantify the impacts of restricted head movement on performance capabilities. Additional head range of motion data is presently being gathered at ECBC to assess the impacts of IPE wear on basic head and body movements. However, this new data set will not be able to advance the knowledge base with regard to how movement restrictions due to a respirator may or may not impact task performance because its primary purpose is to establish body range of motion limits due to IPE.

3.2.5 Cognitive Mental Processing.

Efforts that examined the effects of IPE on cognitive abilities report substantial degradation. In general, there is a tendency for IPE to cause an increase in reaction time but a decrease in error rate. This speed-accuracy tradeoff is a general response to stress. Many of the IPE cognitive performance studies included complete ensembles; therefore, results cannot be directly attributable to respirator wear alone. The few respirator wear-only studies that exist report little, if any, performance effects for a variety of cognitive tasks.[7,8,9,10]Results from the DTRA funded project BA07PRO103, “Human Performance of Personnel in CB Ensembles” may

provide additional insights with regard to the cognitive mental processing capability during respirator wear once it is completed in FY10. Progress on this FY07 initiated effort is unknown at this time.

3.2.6 Comfort.

The REM application included an algorithm for the comfort performance capability. For respirator wear, comfort was assumed to have the main components of breathing comfort and thermal comfort of the face. The impacts of each component were dependent upon task fatigue-endurance rankings. Finally, the REM assumed a temperate ambient environment. The primary shortcomings for the REM comfort capability included development and utilization of an unverified capability scale and a reliance upon very limited data sources that used widely varying subjective scales, respirator wear conditions, and work rates for quantifying comfort. Review of data sources subsequent to those used for the REM demonstrated better variable controls and utilization of a uniform subjective scale for quantifying subjective comfort. Also, attempts to quantify respirator comfort according to additional factors such as head harness design and nose cup design suggest that overall subjective comfort of a respirator could be made up of thermal comfort and mechanical design comfort factors, which includes the original breathing comfort component. Because the comfort performance capability is considered to be important for quantifying human performance during respirator wear, the data obtained after those used in the REM development were compiled for additional analysis and examined for usage in a viable performance algorithm. These findings will be addressed in greater detail in another section of this report.

3.2.7 Dead Space.

The respirator dead space performance capability is relevant only during conditions of respirator wear. Dead space is defined as the volume of air that is re-inhaled from the preceding exhalation.[11] However, many refer to respirator dead space as the fractional concentration of carbon dioxide during inhalation (F_ICO_2). At rest, the volume of carbon dioxide produced ($\dot{V}CO_2$) is approximately 0.2 L/min. Incomplete removal of CO_2 during exhalation under respirator wear conditions can cause an amount of CO_2 above atmospheric levels to be re-inhaled during the following inhalation. Exercise compounds the effects of respirator CO_2 accumulation due to increased metabolic production of CO_2 which may result in much higher CO_2 retention. During moderate to heavy exercise, $\dot{V}CO_2$ can increase to 1.65-2.0 L/min while during maximal exercise $\dot{V}CO_2$ can exceed 4.0 L/min. Effects of breathing high CO_2 (i.e., hypercapnea) are significant. Hypercapnea can result in a decrease in cerebral cortex excitability, release enough catecholamines from the sympathetic nervous system to cause cardiac arrhythmias, and reduce cardiac contractility. Hypercapnea also increases pain threshold through its effects on the central nervous system. All of the above can promote problems with the ability to think clearly, have a negative impact on the cardiovascular system, and reduce the ability to feel pain. Factors that influence respirator dead space include the existence of a nosecup or air-channeling inner mask, nosecup volume, internal airflow pathways, airflow turbulence, and fit. An attempt to relate nominal nosecup dead space volume to effective dead volume (a function of tidal volume, F_ICO_2, and end-tidal CO_2) and performance was included in the REM. The approach utilized in the REM application was limited to empirical results for a single performance study conducted by Johnson et al.[12] The findings from this study indicated a significant effect of dead volume on <u>performance</u>, but the correlation between

the two variables suggested that effective dead volume accounted for only one-third of the variance in performance during exercise. Despite recommendations to better quantify the impacts of sequential changes in either dead space volume or F_ICO_2 on performance at varying work intensities since the end of the REM project, no additional reports have been found.

3.2.8 Depth Perception/Visual Binocularism.

The signals from the two eyes must be routed to allow either eye to have access to the processing mechanisms for position, shape, color, etc. At the same time, information as to the eye of origin must be retained for the purposes of stereoscopy (depth perception). There is little data to suggest that depth perception would be negatively altered during respirator wear. Respirator wear has been shown to improve stereoacuity independent of gender, time of measurement and exercise intensity.[13] No new data were found to change the applicability of this performance capability to conditions of respirator wear.

3.2.9 Expiratory Resistance.

The REM application included an algorithm for an expiratory resistance performance capability, which is relevant only for conditions of respirator wear. The review of data sources subsequent to those used for definition of the original capability found relevant data for improving the knowledge base with regard to understanding how respirator exhalation resistance impacts performance.[14,15] However, the data are still limited to work intensities which. are expected to have the greatest impact on respiration according to the Johnson and Cummings model.[2] Even so, the newer data were compiled for additional analysis and examined for usage in a viable algorithm for quantifying human performance due to respirator exhalation and inhalation resistances.

3.2.10 Hearing Threshold-High Frequency.

No meaningful updates for this performance capability with regard to respirator wear and performance have been identified at this time. A viable connection between one or more mask design parameters and hearing threshold remains to be found.

3.2.11 Hearing Threshold-Low Frequency.

No meaningful updates for this performance capability with regard to respirator wear and performance have been identified at this time. Limited data for low frequency hearing threshold during respirator wear indicates no statistical or practical significant effects on performance.[4] A viable connection between one or more mask design parameters and hearing threshold remains to be found.

3.2.12 Static Visual Acuity.

Respirator lens/visor materials are generally designed with clear enough lens materials to have no impact on visual acuity. Other factors such as moisture condensation, lens deposition of fine particles, liquid or solid material clinging to the lens, lens abrasion, and lens discoloration from normal usage may impact visual acuity to a degree depending upon the severity of each. The data that exists for estimating performance changes due to visual acuity generally reports meaningful changes for visual acuities worse than 20/100. A linkage between lens material characteristics and visual acuity needs to be investigated to provide useable data

for the static visual acuity capability. Additional work needs to be done with this in mind before the capability has merit.

3.2.13 Visual Mental Processing.

Decrements in target detection and monitoring due to IPE are widely reported. However, many of the studies that were evaluated included the complete MOPP IV configuration, thus limiting applicability of findings to respirator only impacts on performance. In general, there appear to be little performance and psychophysiological effects of respirator wear for a variety of visual mental processing tasks. Reported performance decrements in visual tracking and monitoring involved tasks where respirator wear interfered with sighting devices.[16] No additional data has been gathered to assess the impacts of respirator or respirator-sighting device interactions on visual mental processing performance.

3.2.14 Psychomotor Mental Processing.

Psychomotor performance involves motor behavior, typically combining manual manipulation and decision making, and forms the basis of many repetitive work tasks. Potential factors being representative of the types of performance required while wearing a respirator include arm-hand steadiness, control precision, finger dexterity, and reaction time. Literature reports indicate that respirator wear degrades speed of movement more than accuracy, particularly for large motor movements.[10] Also, impacts on steadiness and large movements appear to be greater than for movements requiring precision.[6,10] However, many of the studies that were evaluated included the complete MOPP IV configuration, thus limiting applicability of findings to respirator only impacts on performance. No new data were found to change the applicability of this performance capability to conditions of respirator wear.

3.2.15 Fatigue-Endurance.

As discussed, the Johnson and Cummings[2] working model was implemented in the REM model by categorization of task workloads based on a fatigue-endurance scale value and applying related capability algorithms to estimate task performance. The original ORCA fatigue-endurance capability was used as a means to match task aerobic performance requirements with individual soldier cardiorespiratory capacity. The ORCA scale value was based on run time for two miles. The REM scale values were derived from SME definitions of maximal aerobic capacity ($\%\dot{V}O_2max$) for low, moderate, and high intensity work. This approach provided a means for quantifying work intensities of the various ORCA adapted tasks. However, a preferred means for accounting for work task intensities in estimates of human performance would be to include work rate as a variable in predictive algorithms. Unfortunately, there remains a data gap in understanding the specific impacts of work intensity on all pertinent performance capabilities for respirator wear. Until additional data become available, assumptions will have to remain in place for determining work intensity impacts on performance as well as for gauging performance capability requirements as a function of workload.

3.2.16 Inspiratory Resistance.

Adequate data existed for the REM application to show that when work rates remain constant at levels of 80-85% of $\%\dot{V}O_2max$, performance times are linearly related to respirator inhalation pressures quantified at flow rates of 85 L/min. Research completed since

then shows similar trends for inhalation resistances. However, the data are still limited to work intensities that are expected to have the greatest impact on respiration according to the Johnson and Cummings model.[2] The newer data were compiled for additional analysis and examined for usage in a viable algorithm for quantifying human performance due to respirator inhalation resistance. Consideration has been given to the fact that inhalation and exhalation resistance are inherent to respirator wear and could be combined as a single breathing resistance performance capability.

3.2.17 Visual and Peripheral Field of View.

Reports of the effects of narrowed FOV on exercise performance have not been found. However, several reports contain data that report general decrements in FOV due to respirator wear and impacts of reduced FOV on specific daily activities such as rifle firing.[13,17-19] It is anticipated that performance decrements associated with FOV will be more important for visually demanding tasks at low to moderate work intensities. Usage of system sighting devices will also impact FOV capabilities. Newly acquired data have been compiled and analyzed to try to establish performance relationships that can be beneficial for enhancing respirator performance estimates based on FOV.

3.2.18 Speech Intelligibility.

This performance capability addressed respirator wear impacts on speech sound transmission. The primary measure of speech intelligibility is the Modified Rhyme Test word recognition score. Ample testing has been performed to quantify decrements in speech intelligibility due to respirator wear. However, there is little consistency among reports with regard to background noise conditions, speech signal strength, and distance between speaker and listener panels. In addition, the fidelity of the Modified Rhyme Test for quantifying speech intelligibility is questionable. Additional data have been acquired to permit a new assessment of speech intelligibility during respirator wear.

3.2.19 Thermal Burden.

Multiple efforts have been made to quantify the thermal load imposed by respirator wear.[20-22] Reported results indicate that respirator and hood wear during exercise in the heat elevates whole body sweat rate and mean skin temperatures compared to unmasked conditions. Most reports also show that heart rates tended to be higher during respirator wear. However, no consensus as to the impacts of respirator wear on core temperatures during exercise in the heat has been established. Several additional investigations, historical and recently complete, that have been reviewed suggest that the physiological thermal load attributable to a respirator is negligible. The majority of the research supports the notion that the primary thermal effect of wearing a respirator is subjective discomfort. As such, thermal comfort and mask comfort data from several studies were compiled in the same database developed for general mask comfort and analyzed collectively to determine if any reasonable estimates of comfort due to mask wear are possible based on current data. The methods used for this analysis are presented elsewhere in this report.

Based on the comprehensive review of REM human performance capabilities and the existing knowledge base established subsequent to REM development, a reduced list of capabilities was chosen to include only those capabilities with adequate empirical data to support psychophysiological based estimates of human performance under conditions of respirator wear. Therefore, development of revised or new performance estimates for the

following practical performance capabilities was attempted: breathing resistance (inhalation and exhalation resistance), comfort (including thermal and mechanical comfort), vision (primarily FOV with and without sighting systems), and communications. Development of a performance algorithm to account for the impacts of system weight or mass on performance was also attempted.

3.3 Updated Performance Algorithms.

Algorithm development was limited primarily by the availability of data linking performance with respirator design components. Therefore, any revisions to REM performance algorithms or development of newly defined algorithms included design parameters shown to have merit. The algorithms presented herein are considered to be draft revisions or initial attempts for estimating performance under conditions of respirator wear. Data represent results for fielded (primarily M40A1 and MCU-2/P) or prototype full-facepiece air-purifying respirators (primarily developmental versions of the JSGPM). Values for the 90% solution for development of next generation respirator performance standards were estimated where plausible. Details provided for the development of each performance algorithm include assumptions and background information, methods utilized for data manipulation and analysis, results, limitations for application of the findings, and recommendations for future research.

3.3.1 Vision.

3.3.1.1 Assumptions and Background.

- The primary vision capabilities related to performance during respirator wear are field of view (FOV) and visual acuity
- Field of view is presumed to be most important based upon existing data
- Unencumbered field of view (FOV) spans approximately 200° horizontally by 150° vertically
- Full facepiece respirator wear narrows FOV in horizontal and vertical directions
- Reduced FOV degrades human performance on self-orientation, locomotion, spatial awareness, and visual search tasks
- Eye and head-movement coordination and perception of object size and distance are also impacted by narrowing FOV
- Data for changes in FOV based on respirator wear will provide limited insights on how design impacts FOV
- Data on performance with binoculars and rifle firing will provide limited information on performance of visual tasks

3.3.1.2 Methods.

Data from multiple sources were compiled and analyzed to determine relationships among visual field scores, task performance, and respirator lens design parameters.[18,19,23-27] The list of variables considered for each analysis was as follows:

- FOV area (cm^2) = total area for both eyes within peripheral limits measured using perimetry
- FOV Performance Rating (PR_{FOV}) (%) = relative relationship of FOV area with a respirator to area without a respirato

- FOV_{Binocs} (deg) = FOV when looking through M19 binoculars
- PR_{Binocs} (%) = relative relationship of FOV_{Binocs} with a respirator to area without a respirator
- Scan time with binoculars (ST_{Binocs}) (s) = time to scan targets using M19 binoculars
- Binoculars scan time PR (PR_{BScan}) (%) = relative relationship of scan time with a respirator to time without a respirator
- Rifle fire performance time (PT_{Rifle}) = time to acquire and hit 16 pop-up targets with an M16A2 rifle
- Rifle fire PR (PR_{Rifle}) (%) = relative relationship of rifle fire task time with a respirator to time without a respirator
- Horizontal FOV (HFOV) (deg) = total of visual field peripheral limits along the horizontal axis of a FOV perimeter
- Vertical FOV (VFOV) (deg) = total of visual field peripheral limits along the vertical axis of a FOV perimeter
- Eye relief (cm)
- Lens width (cm) along the horizontal line of sight
- Lens height (cm) along the vertical line of sight

Multiple linear regression analysis showed a significant ($p < 0.005$) and relatively strong ($R^2 = 0.73$) relationship between FOV area and HFOV and VFOV. Therefore, FOV area can be estimated using the following equation:

$$\text{FOV area (cm}^2\text{)} = (1.36 * \text{HFOV (deg)}) + (1.45 * \text{VFOV (deg)}) - 142.70 \quad (1)$$

Estimates for HFOV and VFOV can be derived using values for specific design parameters. Exploratory analysis of the data indicated that the best predictors of HFOV were lens/visor eye relief distance and lens/visor width according to eq 2. The relationship between HFOV and the independent variables was moderate ($R^2 = 0.46$), but significant ($p < 0.05$).

$$\text{HFOV (deg)} = 0.38 - (8.04 * \text{eye relief (cm)}) + (11.76 * \text{width (cm)}) \quad (2)$$

Multiple linear regression showed that lens eye relief did not contribute significantly to estimates of VFOV. The best predictor of VFOV was the lens height design parameter (eq 3), but the relationship between VFOV and lens height was marginally insignificant ($p = 0.06$) and relatively weak ($R^2 = 0.34$).

$$\text{VFOV (deg)} = (9.56 * \text{height (cm)}) + 22.91 \quad (3)$$

The relationship between FOV area and PR_{FOV} is presented in Figure 2. Estimates of PR_{FOV} can be derived from this relationship to quantify FOV area performance decrements as well as to estimate FOV area needed to provide a desired level of visual field performance. The estimated respirator FOV area required to provide a 90% PR_{FOV} is approximately 215 cm^2.

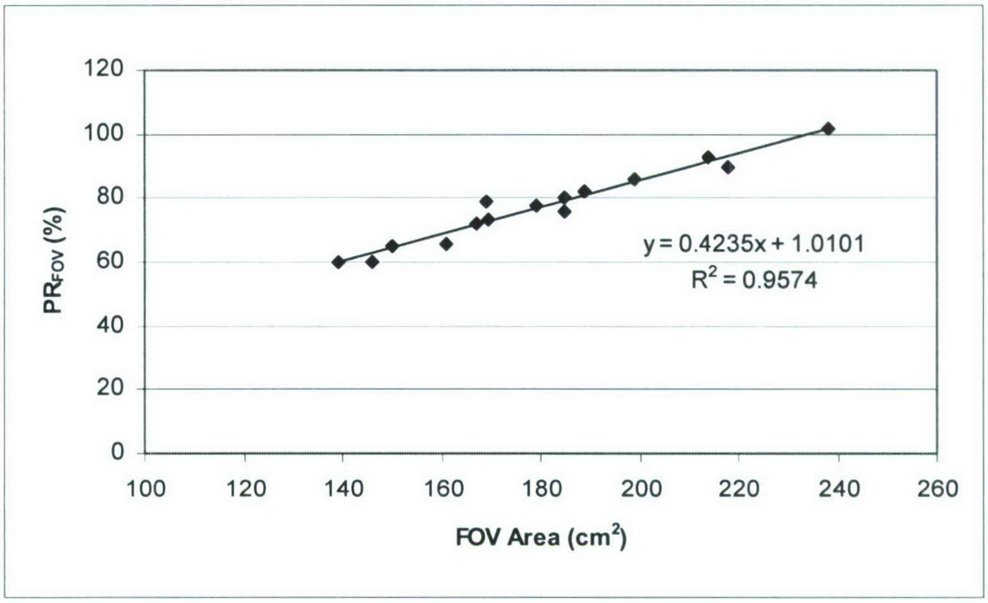


Figure 2. Relationship between Respirator FOV Area and FOV Performance Rating (PR_{FOV})

A strong ($R^2 = 0.96$, $p < 0.001$) linear relationship was observed between respirator eye relief and peripheral FOV when sighting with M19 binoculars. Therefore, FOV_{Binocs} can be predicted from the following equation:

$$FOV_{Binocs} \text{ (deg)} = 6.50 - (0.96 * \text{eye relief (cm)}) \quad (4)$$

The relationship between FOV_{Binocs} and PR_{Binocs} is presented in Figure 3. This relationship can be used to estimate PR_{Binocs} based on FOV_{Binocs} values derived from eq 4. The estimated respirator FOV_{Binocs} required to provide a 90% PR_{Binocs} is approximately 5.7°. Based on eq 4, eye relief required to meet this FOV_{Binocs} is about 0.8 cm.

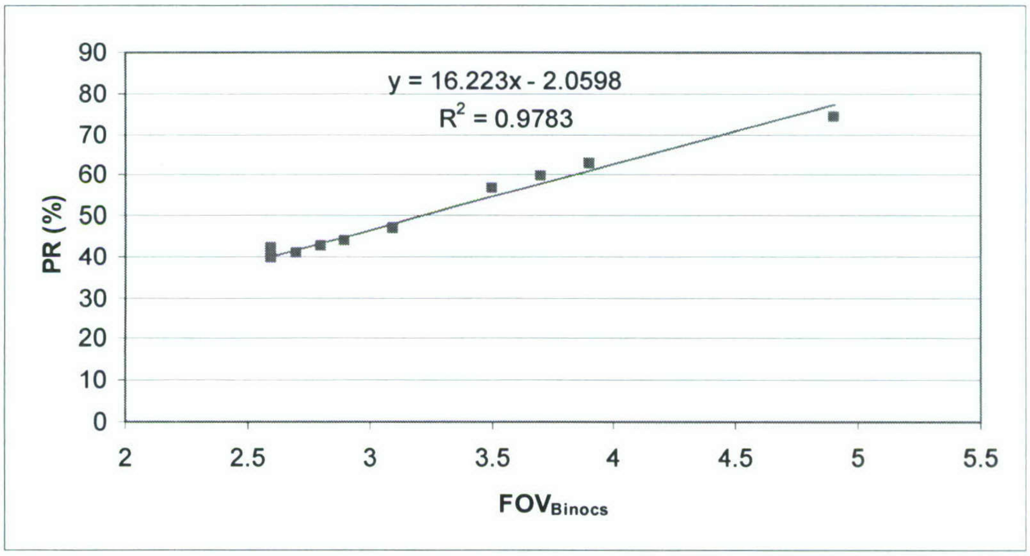


Figure 3. Relationship between FOV_{Binocs} and PR_{Binocs}

Performance degradation as a consequence of reduced field of view due to the combined impacts of respirator wear and binocular usage has been assessed using simulated horizon scanning procedures. The data are based on time required to correctly identify 40 images in a display area approximately 21° by 58° wide when positioned 6.25 m from the display. The relationship between ST_{Binocs} and FOV_{Binocs} was significant ($R^2 = 0.74$, $p < 0.001$) and was described by the equation

$$ST_{Binocs}\,(s) = 59.87 - (5.58 * FOV_{Binocs}\,(deg)) \qquad (5)$$

ST_{Binocs} was not significantly related to any design parameters.

Performance ratings for scanning time with binoculars ranged from roughly 39% to 74% of the unmasked conditions. A significant correlation ($R^2 = 0.85$, $p < 0.001$) between PR_{BScan} and FOV_{Binocs} was observed based on the relationship in eq 6.

$$PR_{BScan}\,(\%) = 27.37 + (11.75 * FOV_{Binocs}\,(deg)) \qquad (6)$$

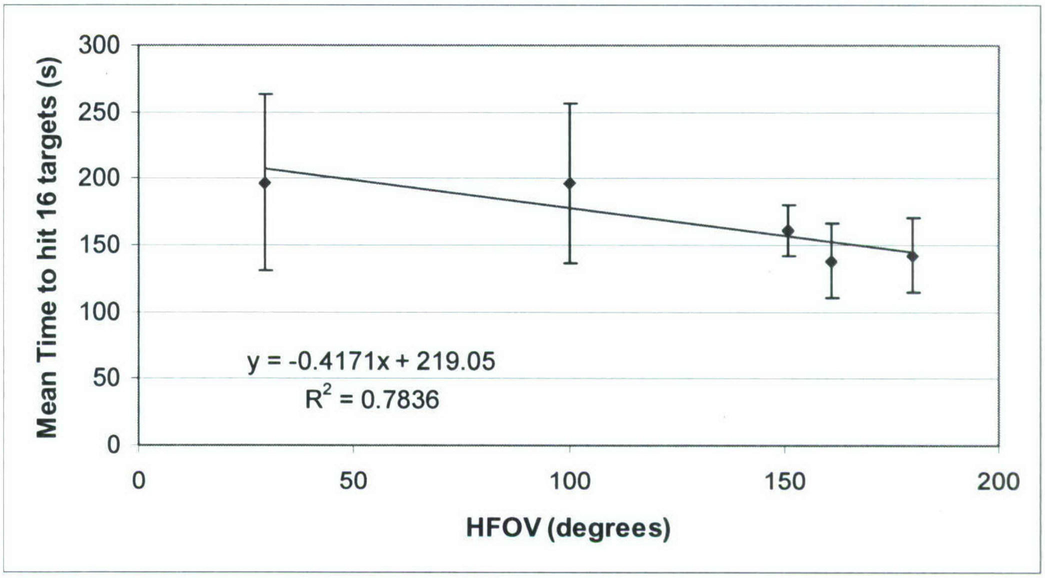
Performance degradation as a consequence of reduced field of view due to respirator wear has been investigated for various rifle firing tasks. Data from similar task scenarios were assessed to determine the impacts of design parameters on the time required to acquire and hit 16 pop-up targets spaced at various locations on a rifle range. Multiple linear regression analysis found no significant relationships between PT_{Rifle} and any of the design parameters. A significant linear relationship ($R^2 = 0.78$, $p < 0.05$) between respirator HFOV and PT_{Rifle} was found (Figure 4). As such, it is possible to estimate PT_{Rifle} using known respirator HFOV values or HFOV values derived from eq 2. A significant linear relationship ($R^2 = 0.82$, $p < 0.05$) was also evident between PR_{FOV} and PT_{Rifle}. Therefore, reasonable estimates of PT_{Rifle} can be derived from PR_{FOV} data.

Performance ratings for rifle firing time ranged from roughly 82% to 89% of the unmasked conditions. These results suggest that the impact of respirator wear on the selected rifle task was relatively minor (degradation of approximately 11% to 18%). Even so, a significant correlation ($R^2 = 0.77$, $p < 0.05$) between PR_{Rifle} and HFOV was observed based on the relationship in eq 7. Likewise, a significant correlation ($R^2 = 0.80$, $p < 0.05$) between PR_{Rifle} and PR_{FOV} was observed based on the relationship in eq 8.

$$PR_{Rifle}\,(\%) = 79.43 + (0.05 * HFOV\,(deg)) \qquad (7)$$

$$PR_{Rifle}\,(\%) = 79.87 + (0.12 * PR_{FOV}\,(\%)) \qquad (8)$$

Based on eq 7, a HFOV of approximately 211° will provide a 90% performance rating for rifle firing. Equation 8 suggests that a PR_{FOV} of about 84% will permit a 90% performance rating for the same task.



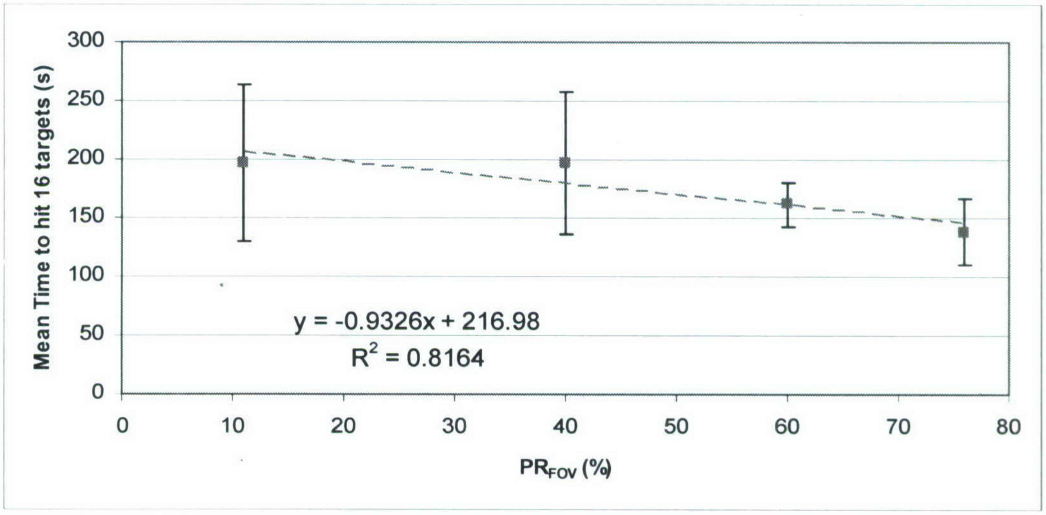


Figure 4. Relationships between HFOV and Time to Hit 16 Targets (Top Graph) and PR_{FOV} and Time to Hit 16 Targets (Bottom Graph)

3.3.1.3 Limitations.

Reports on the impacts of respirator narrowed FOV on exercise performance have not been found.

3.3.1.4 Future Respirator Field-of-View Research.

Additional research should be considered to advance the knowledge base concerning the impacts of respirator field of view on performance. The main purpose would be to establish quantitative relationships between respirator field of view and performance of tasks other than rifle firing and use of binoculars. Performance of small unit tasks should be considered. Suggested research parameters for future work include the following:

- Assess individual warfighter and small unit (2 – 4 persons) task performance
- Test simple and complex visual task scenarios
- Utilize a minimum of three different levels of respirator field of view plus a no-mask control condition
- Test one system with lens parameters estimated to provide the 90% PR_{FOV} (215 cm^2 FOV area)
- Impose different field of view levels using the same baseline respirator system (e.g., JSGPM)
- Attempt to obtain selected fields of view by modifying one lens design component of the baseline respirator system at a time
- Measure task performance times, performance errors, and performance ratings based on field of view and lens design parameters (e.g., HFOV, lens width, eye relief)

3.3.2 Communications.

3.3.2.1 Assumptions and Background.

- Voice communications among respirator wearers is dependent upon background noise and distance between individuals
- Respirator design parameters that impact voice communications include speech transmission device designs (e.g., passive or active), location near the mouth, dead volume, and breathing resistances; additional components such as a protective hood, helmet, and electronic amplification systems will also influence speech sound transmission
- No research has been found that addresses the impacts that each of the respirator design factors has on speech intelligibility during human use trials
- More recent pertinent research includes results reported by Caretti and Strickler,[28] Caretti and Barker,[23] Johnson et al.,[29] and Coyne et al.[30] However, because the results from Johnson et al.,[29] and Coyne et al. [30]were gathered using modified methods of the Modified Rhyme Test (MRT) to measure intelligibility, these data were excluded from initial analysis

3.3.2.2 Methods.

Data from Caretti and Strickler[28] and Caretti and Barker[23] were compiled into a single database and analyzed to explore the following: impacts of background noise on speech intelligibility with and without a respirator, influence of speech transmission device design on speech intelligibility at different background noise levels, and the impact of wearing a hood with a respirator on intelligibility under different noise conditions.

3.3.2.3 Results.

Respirator speech transmission device surface area only impacted speech intelligibility at the lowest background noise tested (40 dBA). Multiple linear regression analysis supported this finding in that only background noise contributed significantly to MRT scores predicted from the variables transmission device surface area, subject speech sound level, and background noise level.

Average MRT scores for all unmasked and masked conditions were plotted against average background noise levels recorded for each test condition. Linear least square regression lines fit separately to the unmasked and mask data produced strong linear relationships. However, these findings were considered to be suspect because estimates of MRT scores in excess of 100% were possible and because each relationship overestimated scores at high background noise levels (> 80 dBA). Upon further examination, each plot suggested an inverse curvilinear decrease in MRT scores with increasing background noise for unmasked and masked conditions. Therefore, separate inverse exponential decay curves were fit to the unmasked and masked MRT data using the equation

$$y = 100+b*(1-\exp(x/c)) \qquad (9)$$

where 100 = the y-intercept (100 is the maximum possible MRT score),
b = slope component, and
c = tau, or the rate of decay of the curve.

The relationships between MRT score and background noise derived from these analyses are presented in Figure 5. The equations for the relationship between MRT score and noise for the unmasked and mask conditions were as follows ($R^2 = 0.99$ for both):

$$\text{Unmasked MRT score (\%)} = 100 + 0.52*(1-\exp(\text{dBA}/18.34)) \qquad (10)$$

$$\text{Masked MRT score (\%)} = 100 + 2.77*(1-\exp(\text{dBA}/24.36)) \qquad (11)$$

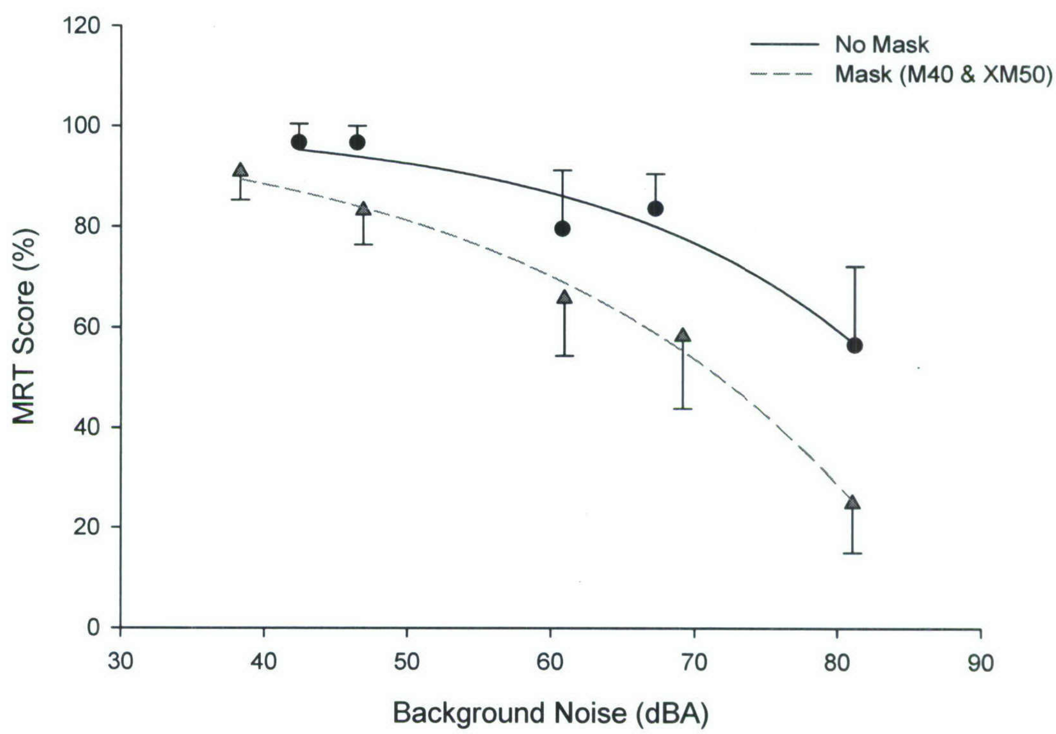


Figure 5. Relationship between MRT Score and Background Noise for Unmasked and Masked Conditions

The relationships of eqs 10 and 11 can be used to estimate unmasked and masked MRT scores for any given background noise. The ratio of unmasked to masked MRT score can then provide a measure of the mask performance rating for speech intelligibility. Calculated results for select background noise levels are presented in Table 4.

Table 4. Estimated MRT Scores and Performance Ratings at Various Background Noise Levels

Background Noise (dBA)	Estimated Unmasked MRT Score (%)	Estimated Masked MRT Score (%)	Performance Rating (%)
20	99.0	96.5	97.48
30	97.8	93.3	95.34
40	95.9	88.5	92.25
50	92.5	81.2	87.76
60	86.7	70.2	81.00
70	76.7	53.7	70.04
80	59.5	28.9	48.51
85	46.6	12.0	25.77

The results presented to this point only provide a means for estimating the impacts of wearing military negative pressure air-purifying respirator systems on speech intelligibility. As previously stated, no significant effects of the surface area utilized by the tested respirators were found across all background noise levels. Additional analyses were performed to assess impact of the protective hoods on intelligibility. The MRT scores obtained from Caretti and Barker[23] for masked conditions with and without hoods are presented in Table V. There were no statistical differences between the No Hood and hooded conditions (both JSLIST and CVC) at either background noise level. Likewise, no differences were found between the JSLIST and CVC conditions. The average MRT scores for the combined JSLIST hood and CVC hood results were 77.2% at 45 dBA and 54.4% at 65 dBA. Thus, conservative estimates of the impacts of a protective hood on MRT scores can be derived by subtracting 6% (83% - 77%) from scores calculated from eq 11 for background noises below 65 dBA and by subtracting 5% (59% - 54%) for noises above 65 dBA.

Table 5. MRT Scores during XM50/51 Wear at Different Background Noise Levels with and without Hoods

Background Noise (dBA)	Hood Condition	Median MRT Score (%)
45	No Hood	83.2
	JSLIST	78.4
	CVC	76.0
65	No Hood	59.2
	JSLIST	56.8
	CVC	42.4

3.3.2.4 Effects of Speech Intelligibility on Performance.

Although it is apparent that good speech communications is needed for effective performance, the quantitative relationship between face-to-face speech intelligibility and mission success has never been established. Intelligibility criteria for voice communications systems listed in MIL-STD-1472F [31] indicate that an MRT score of 91% represents normal acceptable speech intelligibility, whereas a score of 75% is considered minimally acceptable intelligibility. However, these values are only estimates and do not relate performance to intelligibility.

Garinther et al.[32] attempted to quantify the impacts of different levels of speech intelligibility on tank crew performance at various levels of mission complexity. Communication-intensive scenarios were conducted in tank simulators by crews at different levels of speech intelligibility. A gunnery situation in which a tank commander verbally communicated with the gunner to shoot one of four targets represented a relatively simple task scenario. In turn, the gunner had to verbally confirm to the commander that the correct target had been identified and to shoot with the proper ammunition upon command. A second scenario included more complex communication among a company commander outside of the tank and the tank crew consisting of a tank commander, gunner, and driver. The company commander provided verbal instructions to the tank commander for navigation, reporting, and target engagement who then communicated to the crew throughout the task. Tank gunner performance for the gunnery task was scored by percentage of correctly identified and hit targets for the various levels of speech intelligibility. The data in Figure 6 show that gunner performance was reasonably good at speech intelligibility levels as low as 50% where the percentage of targets hit remained over 85%.

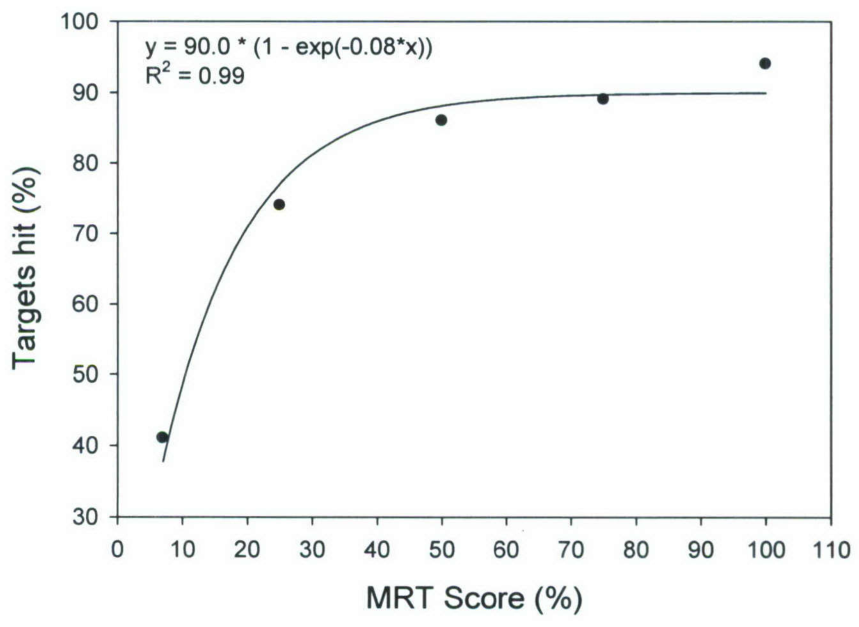


Figure 6. Percent of Time Correct Target was Hit as a Function of Speech Intelligibility (MRT Score)

The exponential relationship between MRT score and percentage of correctly hit targets suggests that speech intelligibility as low as a 75% MRT score will permit a 90% level of performance for the simulated gunnery task.

For the more complex navigation, gunnery and reporting tasks that required more interactive, sequential communication, performance was degraded at higher intelligibility and decreased linearly (Figure 7). These results show that complex scenarios that require conversations among crew members necessitate high speech intelligibility for a high probability of mission success.

Based on the performance results provided by Garinther et al.,[32] it is apparent that as task complexity increases, crew performance begins to decrease at higher speech intelligibility levels. Thus, communications systems that provide for a high degree of speech intelligibility will increase performance. To achieve a mission success rate of 90%, an MRT score of 100% is considered necessary (Figure 7). Conversely, an MRT score of 90% should result in a mission success rate of 80%. These findings fail to define a required level of speech intelligibility for respirator design but emphasize the importance of developing next generation respirators that have negligible impacts on speech intelligibility.

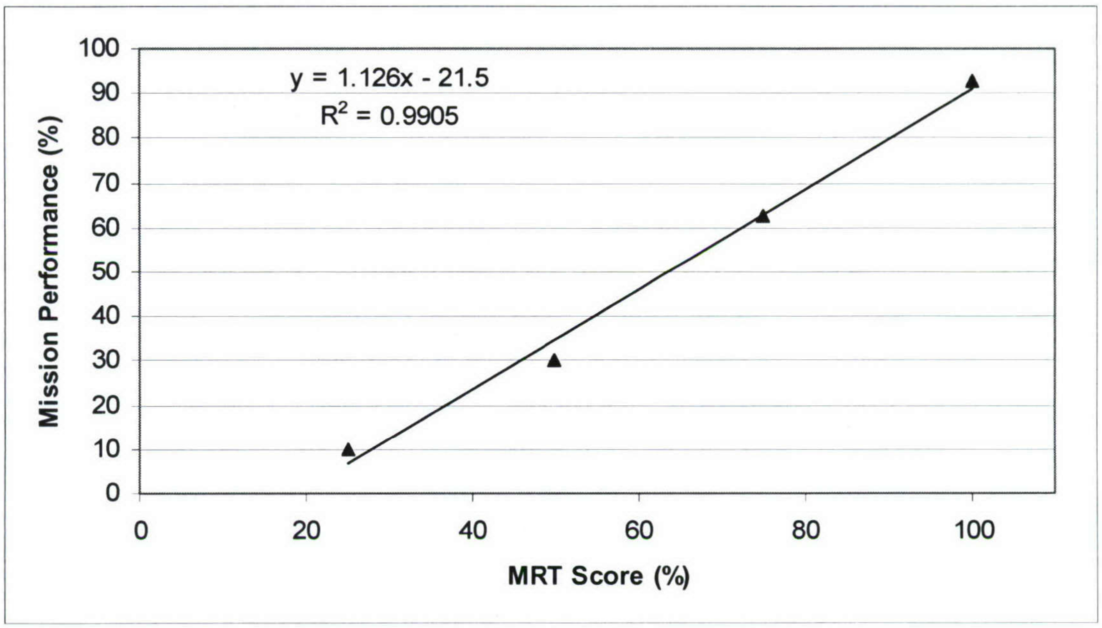


Figure 7. Percentage of Successful Missions as a Function of Speech Intelligibility

3.3.2.5 Limitations.

- The results provided herein are only applicable to unaided face-to-face voice communications between subjects at a distance of 3 m
- The majority of data show performance decrements for select communications measures
- No adequate research has been found to quantify exercise performance decrements associated with communications impediments caused by respirator wear

3.3.2.6 Future Respirator Communications Research.

To advance the knowledge base concerning face-to-face communications with respirators, additional research is recommended. The primary focus of any future work would be to establish quantitative relationships between respirator face-to-face speech intelligibility and task performance. The approach employed by Garinther et al.[32] should be considered as a guide to meet such a goal. However, face-to-face voice communications tasks among small units without the use of electronic devices such as radios, embedded microphones, and on-board vehicle communications systems should be assessed to gain a clearer understanding of the impacts of the design of a respirator's speech transmission device on performance. Suggested research parameters for future work include the following:

- Assess small unit (2 – 4 persons) task performance
- Test simple and complex communications scenarios, but follow exact steps for task completion and do not allow subjects to improvise steps to complete the tasks
- Utilize a minimum of three different levels of respirator speech intelligibility plus a no-mask control condition
- Test under a minimum of two different levels of background noise
- Impose different intelligibility levels using the same baseline respirator system (e.g., JSGPM)
- Attempt to obtain selected intelligibility levels by modifying a single design component of the baseline respirator system (e.g., Caretti and Strickler[28])
- Measure task performance times, performance errors, and performance ratings based on speech intelligibility

3.3.3 Subjective Comfort.

3.3.3.1 Assumptions and Background.

- Subjective comfort is influenced by ambient heat (& humidity), work rate, clothing conditions, and respirator wear
- Overall comfort due to the mechanical properties of a respirator includes factors such as mass, facepiece materials/design, suspension materials/design, nose cup materials/design, airflow characteristics (including breathing resistances), and lens design, among others
- Subjective ratings of comfort with regard to specific respirator properties have been recorded in laboratory and field trial studies using multiple air-purifying respirators and modified systems (e.g., reduced inhalation resistance)
- Respirator comfort factors common to the majority of the literature include facepiece, nose cup, head harness, and breathing comfort; scales of thermal sensation of the face and whole body have also been used to quantify thermal comfort factors
- The vast majority of mask wear studies have been performed in temperate environments
- Almost all data on the effects of high ambient heat (> 95 °F, 60% RH) and CB protective clothing wear on performance are for less than 2 hr of duration because subjects simply could not continue performing or reached thermoregulatory safety end points (e.g., $T_C > 39$ °C)[33]

3.3.3.2 Methods.

Subjective ratings of facepiece, nose cup, head harness, and breathing comfort, as well as thermal sensation, from three studies were compiled and re-analyzed to assess the impacts of these parameters on overall respirator comfort.[20,34,35] Subjective responses were collected at 5 min or 10 min intervals during each study for up to 120 min of testing. Each study involved performance of different tasks, wear of various air-purifying respirator models and modified systems, as well as different environmental conditions. However, the average work rates over time were comparable. None of the data collected under conditions of helmet wear were utilized. For the only study that included exposure to a hot environment,[20] data for overall subjective comfort based on different PPE conditions were collected at 10 min intervals during up to 120 min of testing that involved seated activities and treadmill walking at 45% of $\dot{V}O_2max$ under temperate and hot environmental conditions (estimated average external work rate of approximately 40 W). Subjective comfort and thermal sensation scores for all of the studies were based on the following scales:

Comfort Scale		Thermal Sensation Scale	
10 –	Very, very comfortable	0 –	Very cold
8 –	Very comfortable	1 –	Cold
6 –	Fairly comfortable	2 –	Cool
4 –	Fairly uncomfortable	3 –	Slightly cool
2 –	Very uncomfortable	4 –	Neutral
0 –	Very, very uncomfortable	5 –	Slightly warm
		6 –	Warm
		7 –	Hot
		8 –	Very hot

Multiple linear regression analysis was completed to determine the significance and relative contribution of environmental conditions (based on WBGT), facepiece, nose cup, head harness, breathing comfort, and thermal sensation of the face on overall subjective comfort ratings. Correlations between facepiece, nose cup, head harness, and breathing comfort and time were also assessed independent of specific task and respirator conditions.

3.3.3.3 Results.

Initial analysis indicated that WBGT did not contribute significantly to estimates of overall respirator comfort ($p=0.66$). However, a review of the dataset suggested a trend in differences among comfort parameters based on the range of WBGT values under which the data were collected. Therefore, data were analyzed separately for WBGT temperatures ≤ to 25 °C (77 °F) and above 25 °C because this temperature fell in the middle of the range of WBGT conditions.

For data obtained at WBGT conditions below 25 °C, multiple linear regression results found a significant linear relationship for overall comfort ($R^2 = 0.81$, $n = 693$, $p < 0.01$) according to the equation

$$Comfort_{\leq 25} = 0.59 + (0.06*TS_{face}) + (0.20*facepiece) + (0.29*nose\ cup) + (0.25*harness) + (0.22*breathing) \quad (12)$$

where TS_{face} is thermal sensation of the face,
facepiece is subjective rating of facepiece comfort (unit less),
nose cup is subjective rating of nose cup comfort (unit less),
harness is head harness comfort rating (unit less), and
breathing is breathing comfort score (unit less).

Multiple linear regression results for data collected under WBGT conditions in excess of 25 °C also produced a significant linear relationship for overall comfort ($R^2 = 0.88$, $n = 423$, $p < 0.01$) defined by the equation

$$Comfort_{>25} = 0.40 + (0.12*TS_{face}) + (0.17*facepiece) + (0.32*nose\ cup) + (0.17*harness) + (0.36*breathing) \quad (13)$$

To obtain estimates of comfort from eqs 12 and 13, data for the individual respirator comfort factors are needed. These can be derived using the relationships between each property with time of measurement according to the equations of Table 6. Once determined, these estimates can be used in either eq12 or eq 13 to obtain an estimate of subjective comfort due to respirator wear.

Table 6. Relationships between Respirator Comfort Factors (y) and Time (x) for Wear Conditions above and below 25 °C WBGT

Comfort Factor	WBGT ≤ 25 °C	WBGT > 25 °C
TS_{face}	y = 0.0055x + 4.558	y = 0.0173x + 5.2404
Facepiece	y = -0.0036x + 5.8608	y = -0.0251x + 7.1971
Nose cup	y = -0.0003x + 5.3633	y = -0.0201x + 6.9705
Harness	y = -0.0194x + 6.3625	y = -0.0293x + 6.9523
Breathing	y = -0.0062x + 5.9238	y = -0.0271x + 6.9617

The numbers derived from eqs 12 and 13 will only provide estimates of comfort during respirator wear according to the comfort scale presented previously. However, determination of performance decrements in comfort due to a respirator cannot be calculated using the typical performance rating ratio of masked to unmasked results because *no* data for comfort properties of a facepiece, head harness, or nosecup are plausible without the mask. Also, data for breathing comfort and thermal sensation of the face is very limited for the unmasked conditions completed in the studies used for the present analysis. Even if data were available for all of the comfort parameters for unmasked conditions, the only plausible performance rating calculations that would be possible would be decrements in subjective comfort score due to a mask. Such estimates will give no information about how task performance may be impacted by changes in comfort due to mask wear. Unfortunately, no data have been found that provide direct linkages between mask comfort and task performance. Likewise, differences in comfort scales, work rates, and exposure times among other literature sources prevent adequate inferences or comparisons of results from other literature sources. Additional research will need to be implemented to determine the impacts of mask comfort on task performance.

3.3.3.4 Limitations.

- No relationships between mask components and task performance have been found
- The data do not relate mask components and comfort ratings
- The results are based on data from limited numbers of subjects
- Data can not be generalized for exposure to environmental conditions, work conditions, and wear durations that differ dramatically from those in which they were obtained

3.3.3.5 Future Respirator Comfort Research.

Significant work is needed to improve the knowledge base concerning respirator wear. The main purpose of any future work would be to establish quantitative relationships between respirator comfort and task performance. Suggested research parameters for future work include the following:

- Assess individual warfighter and small unit (2 – 4 persons) task performance
- Test simple and complex task scenarios, but follow exact steps for task completion and do not allow subjects to improvise steps to complete the tasks
- Utilize a minimum of three different levels of respirator comfort plus a no-mask control condition
- Test under temperate and warm to hot environmental conditions
- Include trials of low, moderate, and hard work intensities
- Impose different comfort levels using the same baseline respirator system (e.g., JSGPM)
- Attempt to obtain selected comfort levels by modifying a single design component of the baseline respirator system
- Measure task performance times, performance errors, and performance ratings based on comfort
- Include measures of facial skin temperatures, skin wettedness, and in-mask thermal conditions

3.3.4 Breathing Resistance.

3.3.4.1 Assumptions and Background.

- Performance time is impacted by work rate, oxygen consumption rate, environmental conditions, human cardiorespiratory fitness, prior experience with task requirements, and subjective comfort, among others
- Some minimal level of breathing resistance will be present in most respirators
- Respirator breathing resistances have the greatest impact on performance of moderately heavy to very heavy physical work tasks
- No research exists that adequately defines respirator inhalation resistance or exhalation resistance impacts on task performance at multiple work rates
- Previous efforts to predict task performance time across multiple work rates based on respirator wear and its impacts on ventilation and/or oxygen utilization kinetics proved to be marginally successful[36,37]

- Decrements in performance due to inhalation resistance is linear and there appears to be no defining value at which time performance decreases at a greater rate[38]
- Decrements in performance due to exhalation resistance is also linear and no defining value exists at which time performance decreases at a greater rate[15]
- Although the data from Johnson et al.,[38] Caretti et al.[15] and Caretti et al.[15] were deemed to be most pertinent to the subject of breathing resistance impacts on performance, only the data from Caretti et al.[13] assessed performance based on inhalation and exhalation breathing resistances
- Breathing resistance was defined as the resistance measured for a complete respirator system at a constant flow rate of 85 L/min (1.42 L/sec); therefore, the unit of measure for resistance is cm $H_2O \cdot sec/L$

3.3.4.2 Methods.

The data from Caretti et al.[14] did not include a no resistance or control condition. Therefore, individual subject performance times were plotted across each of the different breathing resistance conditions and a line of best fit was fitted to the data. The y-intercept of an individual subject's line of best fit was utilized as their performance time for a theoretical 'zero' breathing resistance condition. Performance ratings were then derived for individual subjects by dividing performance times by the zero resistance performance time and multiplying the result by 100. Multiple linear regression analyses were performed to determine which independent variables did or did not contribute significantly to predictions of the dependent variable performance rating. The following independent variables were considered: inhalation resistance, exhalation resistance, and relative oxygen consumption.

3.3.4.3 Results.

With each of the three independent variables of inhalation resistance, exhalation resistance, and relative oxygen consumption, performance rating estimates were defined according to the following equation

$$\text{Performance rating (\%)} = 81.96 - (4.86 * R_{IN}) - (5.25 * R_{EX}) + (0.27 * \%VO_{2max}) \quad (14)$$

where R_{IN} = inhalation resistance (cm $H_2O \cdot sec/L$),
R_{EX} = exhalation resistance (cm $H_2O \cdot sec/L$), and
$\%VO_{2max}$ = relative rate of oxygen consumption (%).

The correlation coefficient (R^2) for the relationship in eq 14 was 0.69, which was significant at the $p < 0.001$ level. However, relative oxygen consumption did not contribute significantly to the prediction of performance rating ($p = 0.06$).

Based only on the independent variables of inhalation and exhalation resistance, performance rating predictions were defined by the equation

$$\text{Performance rating (\%)} = 109.84 - (5.07 * R_{IN}) - (7.43 * R_{EX}) \quad (15)$$

The R^2 for the relationship in eq 15 was 0.65, which was significant at the $p < 0.001$ level, and both variables contributed significantly to the prediction of performance rating. A plot of eq 15 predicted versus measured performance rating is shown in Figure 8. In general, there appears to be a symmetrical scattering of data around the line of identity (i.e., 1:1 line). The relationship of eq 15 should provide reasonable estimates of performance associated with respirator breathing resistances. However, eq 15 accounts for no more than 65% of the variance in performance rating due to respirator breathing resistances.

Using eq 15 for determining the 90% performance solution requires advanced knowledge of at least one of the breathing resistance variables (i.e., either inhalation or exhalation resistance). Possible initial design parameters include breathing resistance data from legacy respirator systems (e.g., M40A1 and MCU-2/P) or data from the current JSGPM development program. Estimates of performance based on data for the M40A1 and JSGPM LRIP I prototype are presented in Table 7. These findings suggest that the breathing resistances of the current JSGPM prototype would exceed the 90% performance level earmarked for the next generation respirator system, even under extreme breathing conditions. Performance rating estimates based on JSGPM data also suggest that it may be possible to allow for slightly higher breathing resistance values and still attain the desired 90% performance level. This permits additional design flexibility for filtration components and flow pathways, among others.

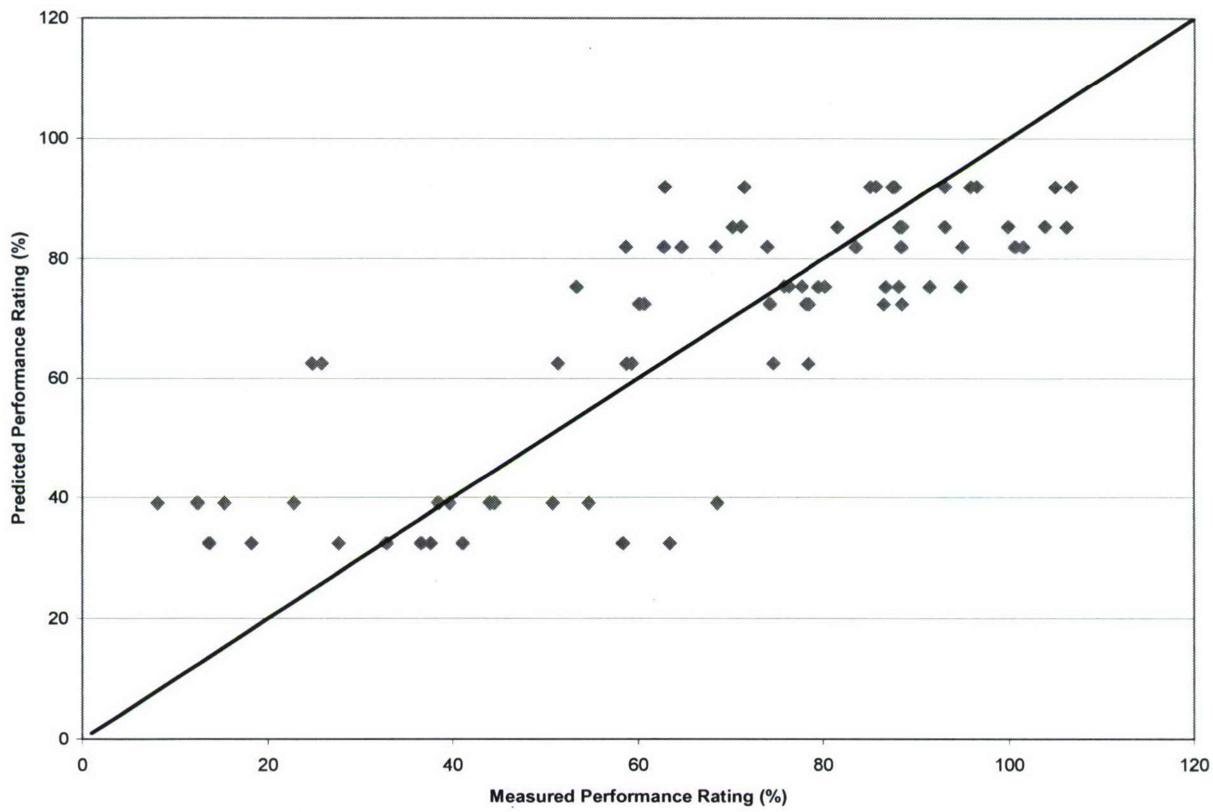


Figure 8. Plot of Equation 15 Predicted versus Measured Performance Ratings
(The solid line represents the line of identity.)

3.3.4.4 Limitations.

- The relationship of eq 15 is only applicable to relative work intensities greater than 75% $\dot{V}O_2max$
- Respirator breathing resistance only accounts for two-thirds of the variance in performance
- Logical boundaries for inhalation and exhalation resistances must be defined to prevent input of meaningless values to derive the 90% performance solution

Table 7. Estimated Performance Ratings (PR) for the M40A1 and JSGPM (LRIP II) Derived from Breathing Resistance Data and the Linear Relationship Defined in Equation 15

	Flow rate		Pressure drop ($mm\ H_2O$)		Resistance ($cm\ H_2O \cdot sec/L$)		
	L/min	L/s	Inhalation	Exhalation	Inhalation	Exhalation	PR (%)
M40A1	85	1.42	45.2	19.9	3.19	1.40	83.23
	105	1.75	59.7	24.6	3.41	1.41	82.10
	125	2.08	77.2	29.9	3.71	1.44	80.39
	145	2.42	96.3	35.1	3.98	1.45	78.85
JSGPM	85	1.42	24.9	6.5	1.76	0.46	97.52
	105	1.75	32.3	8.1	1.85	0.46	97.04
	125	2.08	40	9.8	1.92	0.47	96.61
	145	2.42	49.4	11.7	2.04	0.48	95.88

3.3.4.5 Future Respirator Breathing Resistance Research.

To improve the understanding of the impacts of respirator breathing resistances on performance, further research needs to be implemented. Considering that the majority of existing data has been established for hard work intensities, future work should focus on performance of moderate intensity tasks. Some testing of small unit task performance may be useful, but should not be pursued until individual warfighter performance has been assessed. An evaluation of the performance of the JSGPM respirator compared to the estimates of performance derived from eq 15 for the system should also be considered. Suggested research parameters for future work include the following:

- Assess individual warfighter performance
- Empirical testing with the JSPGM to validate/enhance performance estimates
- Implementing a research program to define respirator inhalation resistance and exhalation resistance impacts on task performance at multiple work rates
- Test the impacts of a 90% solution concept respirator on performance of military tasks/simulation scenarios
  - Include multiple work rates
  - Focus on individual subject performance
- Impose different inhalation and exhalation resistance levels singularly and in various combinations using the same baseline respirator system (e.g., JSGPM)
- Measure task performance times, performance errors, and performance ratings based on resistance parameters

3.3.5 Respirator System Mass.

3.3.5.1 Assumptions and Background.

- Carrying added weight of IPE on the body increases the metabolic cost of exercise compared to the non-IPE condition
- Light loads positioned around the center of mass of the head or body are carried relatively efficiently, however weight carried on the head can become burdensome if excessive and not adequately positioned
- No data that adequately defines the impacts of respirator facepiece mass and center of gravity on task performance is available
- Decrements in work performance due to PAPR helmet weight were assessed by Johnson et al.,[39] albeit without the respirator

3.3.5.2 Methods.

Johnson et al.[39] assessed performance times of treadmill walking at 80 to 85% $\dot{V}O_{2max}$ with four different weighted helmets: 0.54, 1.03, 1.85, and 3.36 kg. A linear relationship between performance time and helmet mass, defined by the equation Performance time (min) = 20.3 – 2.6 * Mass (kg), was found and the relationship was marginally insignificant ($p = 0.07$, $R^2 = 0.71$). The study did not include a no-helmet condition and the performance times of the individual test participants (N = 9) were not available. Therefore, average performance times were plotted across each of the different weighted helmet conditions and a line of best fit was fitted to the data. The y-intercept was then utilized as the average performance time for a theoretical no helmet condition for all volunteers. Performance ratings were then derived for each helmet condition by dividing average performance times by the no helmet performance time and multiplying the result by 100.

3.3.5.3 Results.

Performance ratings based on weighted helmet conditions of the Johnson et al.[27] study were defined by the linear relationship of eq 16.

$$\text{Performance rating (\%)} = 100.2 - 12.6 * \text{Mass (kg)} \tag{16}$$

Despite the lack of statistical significance ($p = 0.16$), performance derived from eq 16 provides a potential means for estimating the impacts of head borne respirator mass based on the current knowledge base. As such, the estimated head borne mass that results in a 90% performance rating is 0.81 kg.

As a comparative check against established research relating load carriage and metabolic cost, estimates of performance were derived from relationships developed by Kamon[40] and Givoni and Goldman.[41] The Givoni and Goldman[41] equation predicts an increase in metabolic rate equal to the ratio of the carried mass to the body mass. For example, if a respirator has a mass of 1 kg and the person wearing it weighs 70 kg, the metabolic work rate will increase 1.4% (1 kg / 70 kg). As there is a proportional relationship between oxygen consumption and metabolic work rate, a percentage increase in metabolic rate will result in a concomitant increase in oxygen consumption. This information may be used with the Kamon[40] equation to provide an estimate of the impact of carried loads on performance rating. The Kamon[40] equation is

$$\text{Performance time (min)} = 120 * \left(\frac{\dot{V}_{O2\max}}{\dot{V}_{O2}} \right) - 117 \qquad (17)$$

where $\dot{V}_{O2\max}$ = the maximum oxygen consumption, L/min

$\dot{V}_{O2}$ = the oxygen consumption, L/min

A performance rating may be determined by finding the ratio between performance time while carrying the load and performance time without the load:

$$\text{Performance rating (\%)} = \frac{120 * \left(1 \big/ \%\dot{V}_{O2load} \right) - 117}{120 * \left(1 \big/ \%\dot{V}_{O2noload} \right) - 117} \times 100 \qquad (18)$$

where $\%\dot{V}_{O2load} = \dot{V}_{O2load} \big/ \dot{V}_{O2\max}$

$\%\dot{V}_{O2noload} = \dot{V}_{O2noload} \big/ \dot{V}_{O2\max}$

Substituting the fact that the $\dot{V}_{O2load}$ is proportional to $\dot{V}_{O2noload}$ ($\dot{V}_{O2load} = c * \dot{V}_{O2noload}$), the resulting relationship is:

$$\text{Performance rating (\%)} = \frac{120 * \left(1 \big/ c * \%\dot{V}_{O2noload} \right) - 117}{120 * \left(1 \big/ \%\dot{V}_{O2noload} \right) - 117} \times 100 \qquad (19)$$

where c = the percent increase in metabolic work rate due to the carried load.

A family of equations may be developed to determine the impact on performance rating of carried loads for different work rates, (i.e., for different $\%\dot{V}_{O2noload}$). The resulting relationship would express performance rating as a function of carried load for a specific $\dot{V}_{O2\max}$. Because the proportionality constant, c, is dependent on the carried mass and body mass, the body mass must either be known or assumed.

Johnson et al.[39] reported that subjects exercised at 80% $\dot{V}_{O2\,max}$ and that their average mass was 71.3 kg. Using these values in eq 19), data were generated for theoretical respirator loads in excess of body mass (zero to 4 Kg). The following regression equation was obtained from this analysis.

$$\text{Performance rating (\%)} = 99.8 - 6.0 * \text{Mass (kg)} \qquad (20)$$

This equation and the relationship derived from Johnson et al.[39] are shown in Figure 9.

From the plot and a comparison of the two eqs 16 and 20, the Johnson, et al.[39] equation predicts a much greater impact of the carried load on performance rating. The estimated head borne mass needed to produce a 90% performance rating using eq 20 is 1.6 kg, which is twice that predicted by eq 16 (0.81 kg). With a lack of agreement between the two equations for estimating performance with added loads it is difficult to settle upon one approach of estimation. Although the performance estimates derived from Kamon's[40] equation were not developed specifically for head borne loads or for respirator wear conditions, shortfalls of the Johnson et al.[39] data were considered to be more significant. Until additional research can be implemented, estimates of the impacts of respirator mass on performance derived from eq 20 provide the best information available at this time.

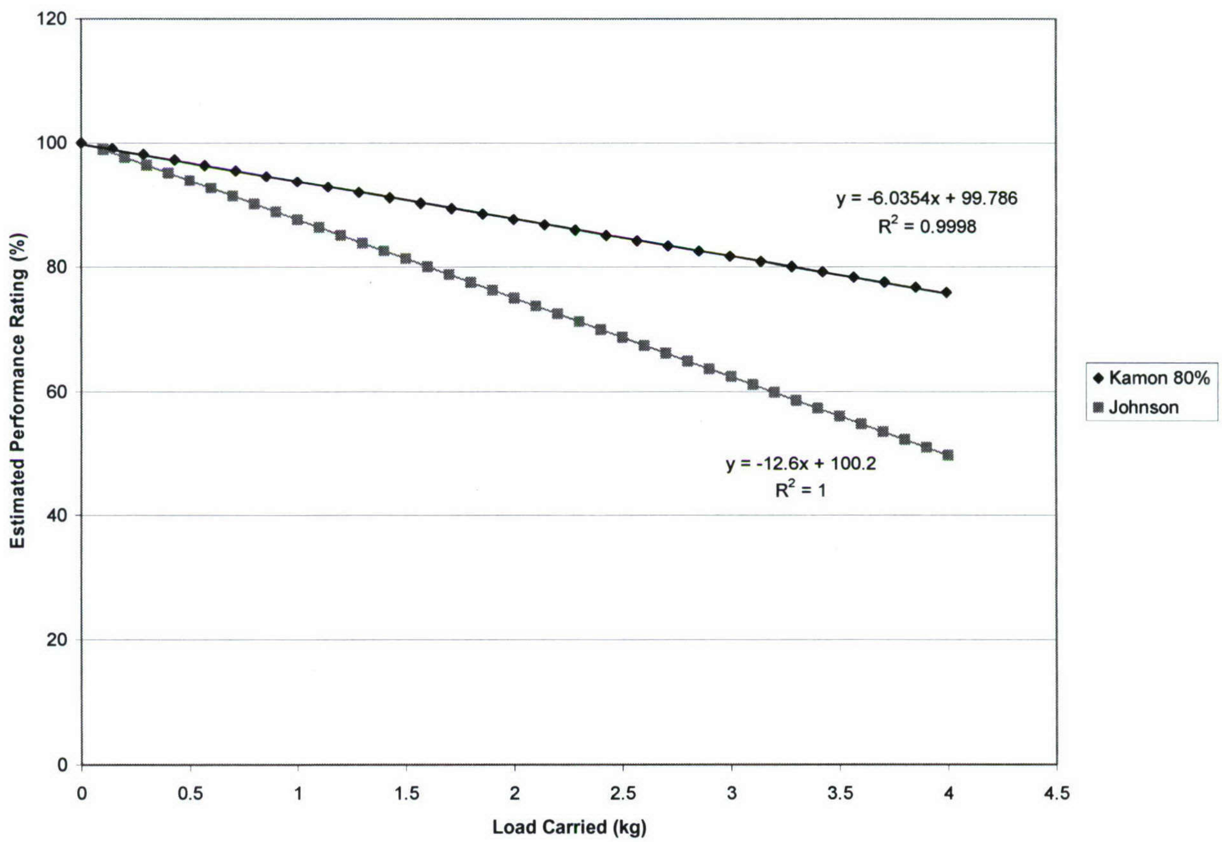


Figure 9. Estimated Performance Ratings due to Load Carried Based on Data from Johnson et al. and Estimates Derived from Equation 19 Using Average Subject Mass from Johnson et al. and a Work Intensity of 80% of Maximal Aerobic Capacity

3.3.5.4 Limitations.

- The relationships of eqs 16 and 20 assume ideal positioning of a respirator on the head
- The relationship represents total head borne mass, so the impacts of a protective helmet or other head borne items can be added to derive total head borne mass

3.3.5.5 Future Research to Quantify Impacts of System Mass on Performance.

Additional research needs to be implemented to establish a clearer understanding of the impacts of respirator weight on performance. Initial efforts should attempt to gather empirical data from previous respirator wear studies and to review the data to determine what can be estimated using predictive models. The degree of human use testing needed beyond such a review can be determined upon completion of the initial task. Regardless, studies need to include actual respirator wear trials to ensure data relevance. Performance of individual warfighter and small unit tasks should be considered. Suggested research parameters for future work include the following:

- Emphasize individual warfighter task performance, followed by analysis of small unit (2 - 4 persons) task performance
- Test performance of low, moderate, and hard intensity tasks
- Scale respirator mass according to performance ratings predicted across work intensities (e.g., 90% performance rating predicted from a 1.6 kg load for a 71.3 kg body weight working at 80% $\dot{V}_{O2\,max}$)
- Evaluate physical and cognitive performance based on objective and subjective measurements
- Utilize a minimum of three different levels of respirator mass plus a no-mask control condition
- Impose different respirator masses using the same baseline respirator system (e.g., JSGPM) with identical center of gravity and moment of inertia
- Attempt to obtain selected masses by modifying a single design component of the baseline respirator system
- Measure task performance times, performance errors, and performance ratings based on respirator loads

4. POSSIBLE INTERRELATIONSHIPS OF RESPIRATOR PERFORMANCE CAPABILITIES

The revised or newly derived performance algorithms for vision, communications, breathing resistance and system mass represent rough estimates of performance based solely on each of the individual performance capabilities. However, respirator wear automatically encompasses all of these performance capabilities with the donning of any system. Therefore, human performance during respirator wear is a function of each of the individual performance capabilities, which can be defined by the equation

$$\text{Performance} = f\,(\text{V, Com, R, M, Cft}) \qquad (21)$$

where V = performance due to vision capabilities,
Com = performance due to communications,
R = performance due to breathing resistance,
M = performance due to system mass, and
Cft = performance due to comfort.

Based on Johnson and Cummings'[2] model of work performance limitations as a function of work rate and other empirical findings, each of the performance factors are expected to have a different impact on performance dependent upon task work intensity. For simplicity, it was assumed that the overall performance level will equal the weighted sum of performance associated with each of the individual performance capabilities, or

$$\text{Performance} = w_1V + w_2Com + w_3R + w_4M + w_5Cft \quad (22)$$

where w_i = weighting factor.

Therefore, possible weighting factors were derived for each of the performance factors according to work rate categories listed in Table 8.

Table 8. Work Rate Categories Defined by $\%\dot{V}O_2max$

Category	Relative Oxygen Consumption
Low	$\%\dot{V}O_2max < 40$
Moderate	$40 \leq \%\dot{V}O_2max < 75$
High	$\%\dot{V}O_2max \geq 75$

Estimates of performance with a respirator could then be calculated according to the following equations for each of the three work rate categories defined in Table 8:

$$PR_{Low} = (0.15*V) + (0.20*Com) + (0.05*R) + (0.05*M) + (0.55*Cft) \quad (23)$$

$$PR_{Mod} = (0.10*V) + (0.25*Com) + (0.20*R) + (0.10*M) + (0.35*Cft) \quad (24)$$

$$PR_{High} = (0.025*V) + (0.025*Com) + (0.65*R) + (0.15*M) + (0.15*Cft) \quad (25)$$

5. CONCLUSIONS

This report addressed the results of FY07 efforts to assemble an improved scientific framework of human performance variables impacted by respirator wear in support of future respirator design efforts. The present results are dependent on the merits of the basic studies used to draft performance capabilities and related performance algorithms. It is painfully obvious that much of the basic psychophysiological data needed to enhance respirator design

requirements remains elusive. The main data gaps across all performance capabilities include little or no knowledge concerning the relationships among respirator design components and performance and the impacts of design parameters on task performance across different work intensities. The impacts of mask design on subjective comfort and subsequent task performance is the capability area with the least amount of reliable information. In this regard, research needs to continue to advance the knowledge base to ensure that next generation respirator designs can be based on robust human factors data.

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